Recent Studies of the Overturning Circulation in Hood Canal

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Introduction

From 1998 through 2000 there have been several hydrographic surveys of Hood Canal as part of the Puget Sound Regional Synthesis Model (PRISM) program and a focused study by the Washington State Department of Ecology (Ecology) in conjunction with the Puget Sound Ambient Monitoring Program. In addition to the standard set of hydrographic properties, dissolved anthropogenic chlorofluorocarbons (CFCs) were measured on a subset of these surveys. These data sets provide a time series which reveal the net overturning circulation in this estuary. The annual cycle of properties in deep Hood Canal is a result of the flushing process and its interannual variability. The conservative behavior of the CFCs make them useful for separating the effects of the physical processes from biological processes which affect the distributions of dissolved oxygen and nutrients.

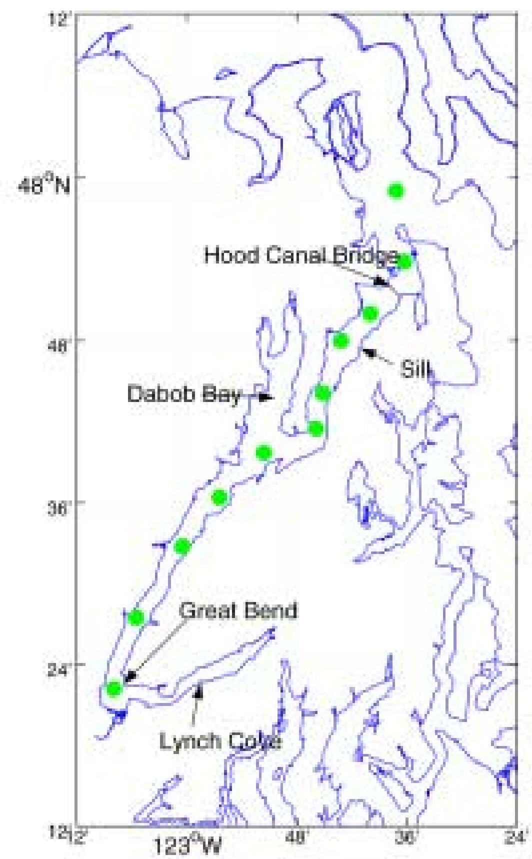


Figure 1 Map of Hood Canal with the locations of the 11 stations. Other features are also labeled.

Hood Canal is a fjord with its mouth located between the two Admiralty sills. A broad sill with depth of approximately 55m separates the deep waters within Hood Canal from the deep waters which are flowing over the Admiralty Sills into Puget Sound from the Pacific Ocean via the Straits of Juan de Fuca. Hood Canal has stronger stratification separating the upper and lower layers than the main basin of Puget Sound.

There is also relatively small river input to Hood Canal. The largest river is the Skokomish which flows into the estuary near the "Great Bend" with a flow of 60 m^3s^{-1}. Several other smaller rivers—Dosewallips, Hamma Hamma, Quilcene, Duckabush, and Kitsap – add another 90 m^3s^{-1} of freshwater to the upper layer. Previous studies of the volume transport of deep waters into Hood Canal (Ebbesmeyer and others 1984; Cokelet and others 1992) have found it to be much smaller than the volume transport into the main basin. These estimates (1000-3600 m^3s^{-1}) correspond to residence times of one to four months for the deep waters in Hood Canal. This can lead to low dissolved oxygen concentrations (less than 5 mg l^{-1}) during the course of the summer over much of Hood Canal. The lowest dissolved oxygen concentrations in the deep waters are usually located at the Great Bend and may be as low as 1.5 mg l^{-1} (Newton and others 1995). The persistence of low dissolved oxygen concentrations within a given year and its areal extent both appear to be increasing during the 1990's (Newton *et al*., 1998).

The recent observations regarding low oxygen concentrations in Hood Canal stimulate the need to understand the relative influence of physical (changes in flushing), biological (changes in natural productivity from nutrient and light variability), and human-induced (nutrient loading/eutrophication, alteration of freshwater delivery) processes on the observed concentrations. Primary productivity has been shown to be highly nutrient-limited during summer (Newton and others 1995), thus processes affecting either natural or added sources of nutrients are important to resolve. In addition, the speed of flushing, its interannual variability, and the factors affecting its rate are central to discerning the role of physical processes in determining oxygen concentrations relative to respiration. In this study, we use dissolved chlorofluorocarbons (CFCs) to trace water mass movement quantitatively, as well as a series of observations on water properties to determine these factors.

CFCs have been used as tracers of ocean circulation and ventilation (for example, Warner and others 1996) for the past 15 years. These compounds are stable in the troposphere and in the water column. Only in regions of anoxia does there seem to be a destruction of CFC-11 (CCl_3F) (Bullister and Lee 1995). The usual assumption for using these anthropogenic tracers is that they enter the ocean through gas exchange at the surface where their solubilities as functions of salinity and temperature are well-known. The concentrations of these compounds in the atmosphere has increased nearly exponentially as a function of time through the 1990s. Waters are assumed to leave the surface with CFC concentrations in equilibrium with the atmosphere, thus providing a method of determining "age" of a subsurface water mass.

It should be noted that this study is of the net circulation averaged over many tidal cycles. The tidal currents are much stronger than the motions associated with the density-driven, overturning circulation. In addition, the data has been collected without consideration of the tidal cycle.

Data

The data for this study is the result of 15 occupations of 11 stations (Fig. 1) between April 1998 and June 2000 from the Admiralty Sill region to the Great Bend. At each station, a 12- or 24-position rosette with 10-liter Niskin bottles was deployed to collect water samples for analyses of dissolved oxygen, nutrients (phosphate, silicate, nitrate, nitrite, and ammonium), chlorophyll, and other dissolved compounds. A Seabird Model SBE 911+ CTD was mounted on the rosette for continuous profiles of salinity and temperature with depth. Additional sensors on the rosette included a Sea Tech fluorometer, a Sea Tech 25-cm transmissometer, and a YSI dissolved oxygen sensor. The 15 cruises were carried out from either the *R.V. Clifford A. Barnes* or the *R.V. Thomas G. Thompson*. These cruises were PRISM studies (6), UW OCEAN 460 class senior project studies (2), and part of a focused study by Ecology (7 cruises).

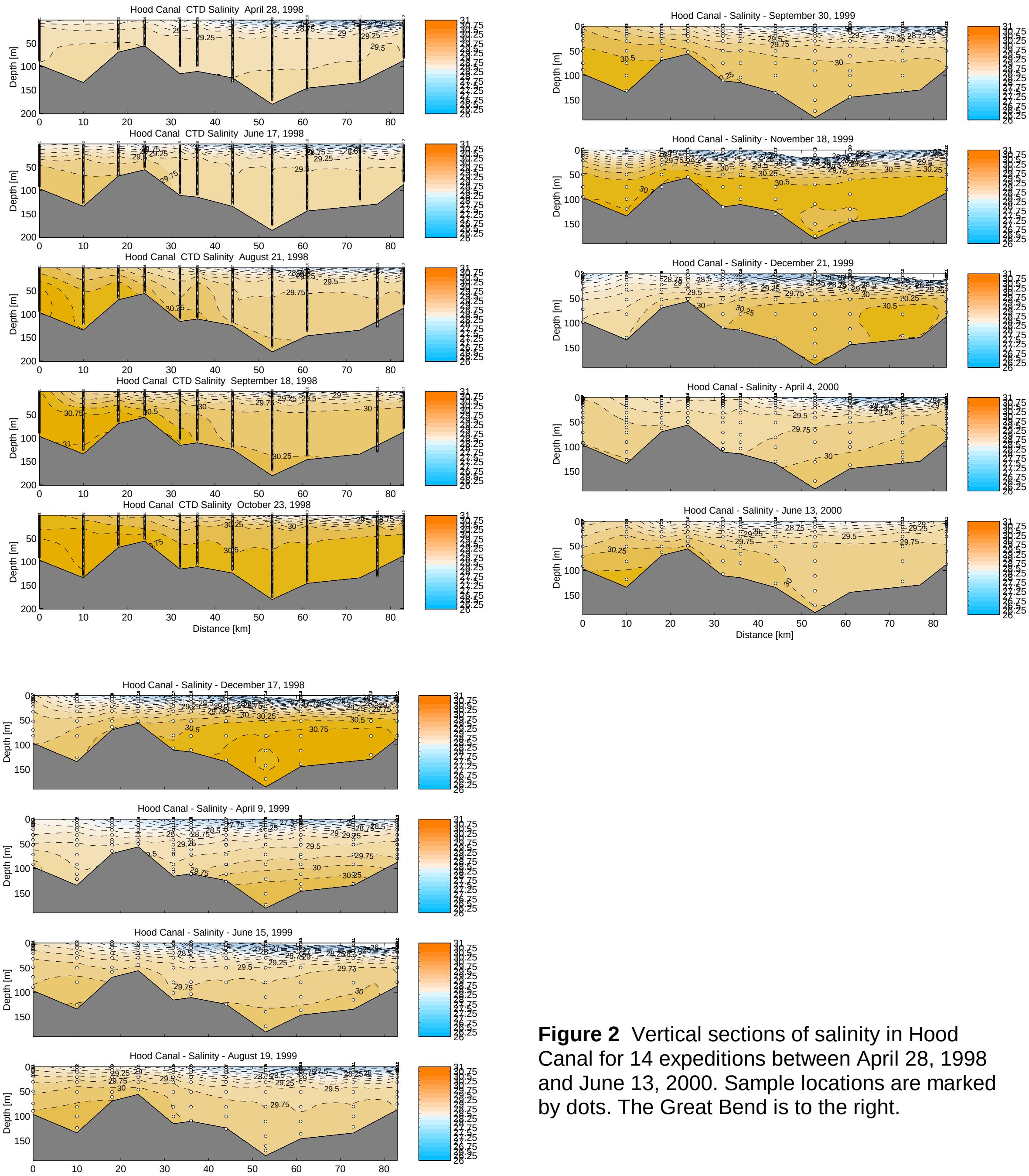
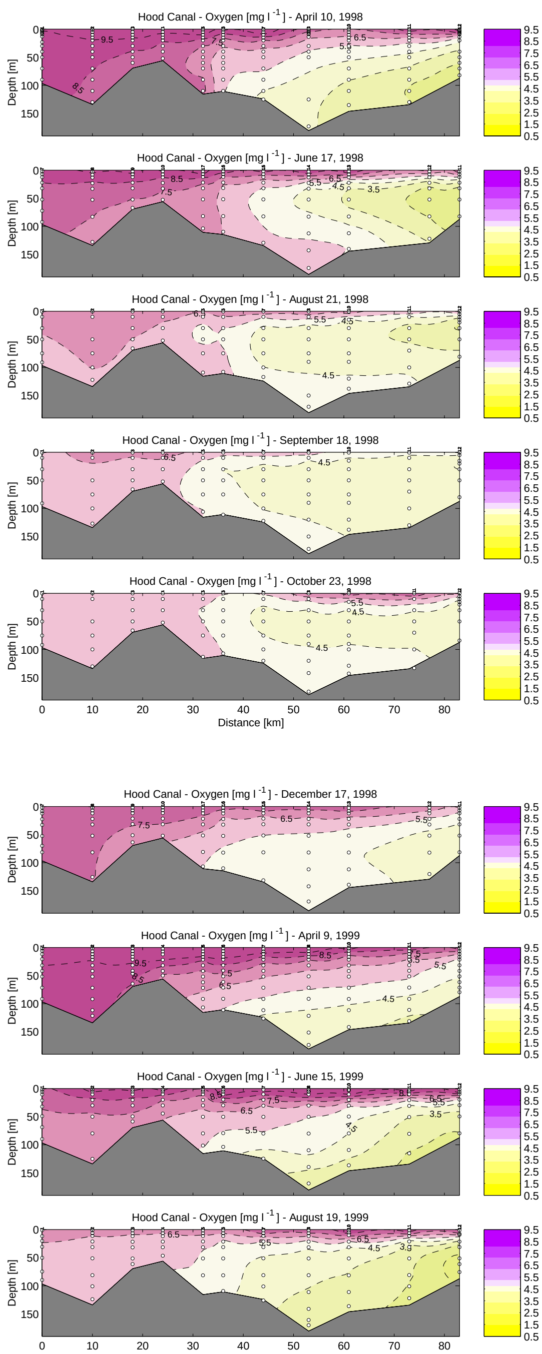


Figure 2 Vertical sections of salinity in Hood Canal for 14 expeditions between April 28, 1998 and June 13, 2000. Sample locations are marked by dots. The Great Bend is to the right.

Dissolved CFCs were measured during eight of these expeditions. In this study, 35 to 40 samples per cruise were collected in 100-cc ground glass syringes with stainless steel stopcocks for analysis in the laboratory at UW. A slightly-modified version of the standard purge-and-trap technique followed by measurement using a Hewlett-Packard HP5890II gas chromatograph with electron capture detector (Bullister and Weiss 1988) was used for the CFC measurements. Concentrations are reported on the SIO 1993 calibration scale.



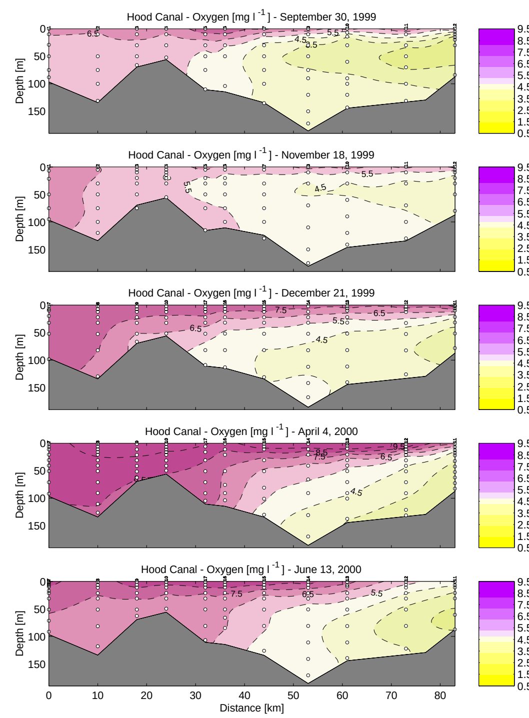


Figure 3 Vertical sections of dissolved oxygen (mg l-1) for 14 occupations of Hood Canal stations between April 28, 1998 and June 13, 2000. The Sample locations are marked by dots. Admiralty Inlet is on the left and the Great Bend on the right.

Results

The data have been gridded using an optimal estimation technique (Roemmich, 1983) and machine-contoured. There are many properties that illustrate the overturning circulation. Sections of salinity (Fig. 2) reveal relatively low salinity water (<29.7) in the deep portion of the basin in April 1998. Higher salinity water begins to intrude between June and August 1998, completely filling the deep layer with relatively high salinity water (>30.8) by December 1998. This water is saltier and denser than the inflowing water between December 1998 and April 1999. This results in a 3-layer system where the deepest layer becomes isolated from the overturning circulation; instead the inflowing water remains at an intermediate depth flowing towards the Great Bend and entraining into the upper layer. There must be mixing between the deep and intermediate layer which eventually decreases the salinity and density of the deep layer to less than that of the inflowing waters which results in the resumption of the two-layer circulation by August 1999. Through Autumn 1999 saltier, denser water fills the deep layer of Hood Canal, however the salinities are lower than those in 1998. The time period between December and April again appears to be characterized by the three-layer system, which returns to the two-layer circulation by June 2000.

The general features of this overturning circulation are consistent with previous measurements in Hood Canal (Collias and others 1974). The major flushing event with high-salinity waters occurs in the autumn. The origin of this high-salinity signal is the upwelling off the Washington coast and propagation of these waters through the Straits of Juan de Fuca into Puget Sound and Hood Canal. The interannual variability in the timing of the cycle and the properties reflect variations in the North Pacific. Kawase (personal comm.) has presented evidence that the reduced upwelling off the WA coast associated with the 1997-98 El Niño appears to have reduced the strength of the flushing in autumn 1997 prior to this study period.

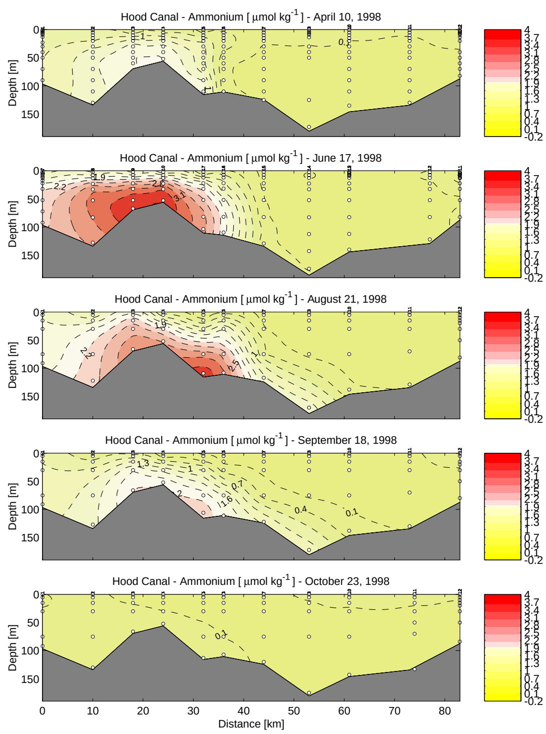


Figure 4 Vertical sections of dissolved ammonium (μmol kg-1) in Hood Canal during April – October 1998. Sample locations are marked by a dot. The Great Bend is to the right. The annual cycle is similar in 1999 and

Dissolved oxygen concentrations measured in April 1998 are consistent with a lack of flushing during the previous autumn (Fig. 3). The lowest values, near the Great Bend, are less than 2.5 mg l^{-1} in contrast to values near 3.5 mg l^{-1} in April of 1999 and 2000. The distributions of dissolved oxygen are consistent with the flushing scenario described for salinity above, but they are complicated by the non-conservative behavior of dissolved oxygen. Respiration of organic matter produced by photosynthesis in the upper portion of the water column which then sinks into the lower layer reduces the dissolved oxygen concentration over time. The upper layer remains oxygenated due to gas exchange, which drives the surface dissolved oxygen concentrations towards solubility equilibrium, and photosynthesis, which produces dissolved oxygen.

The deep waters which spill over the sill are generally a source of higher dissolved oxygen to the lower layer. In instances where the incoming waters are denser than the lower layer, the dissolved oxygen clearly shows the highest values along the bottom and lower values at mid-depth (*e.g.* June 17, 1998). Whereas when the three-layer mode exists, the lowest dissolved oxygen values are found at the bottom and towards the Great Bend (*e.g.* April-June 1999 and 2000). During the course of the summer, dissolved oxygen values decrease as a result of decreased flushing rates and increased primary productivity of the overlying water with the associated increase in sinking particles.

An unexpected finding of these studies is the presence of ammonium at the sill during April to September of each year (Fig. 4). This plume has the highest concentrations (greater than 3.4 μmol kg^{-1}) in August. Its location at the sill indicates that there must be a source at this location. The annual cycle suggests that it is probably of biological origin. Further research is being carried out to understand this plume.

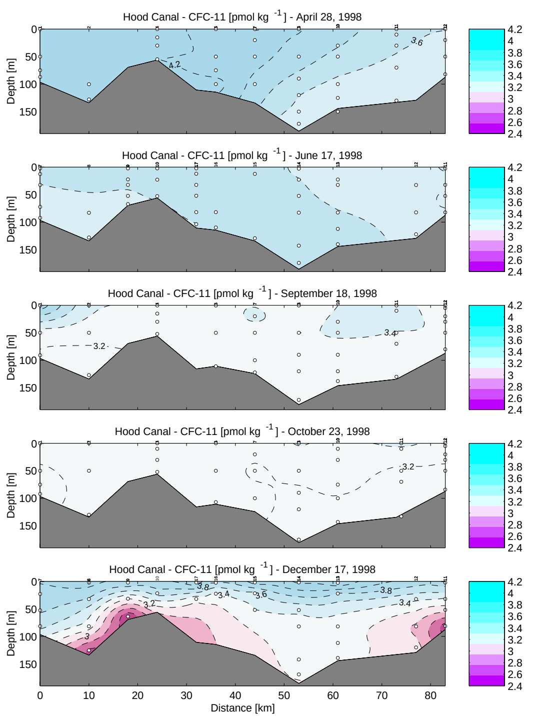


Figure 5 Vertical section of CFC-11 concentrations (pmol kg-1) in Hood Canal for April-December 1998.

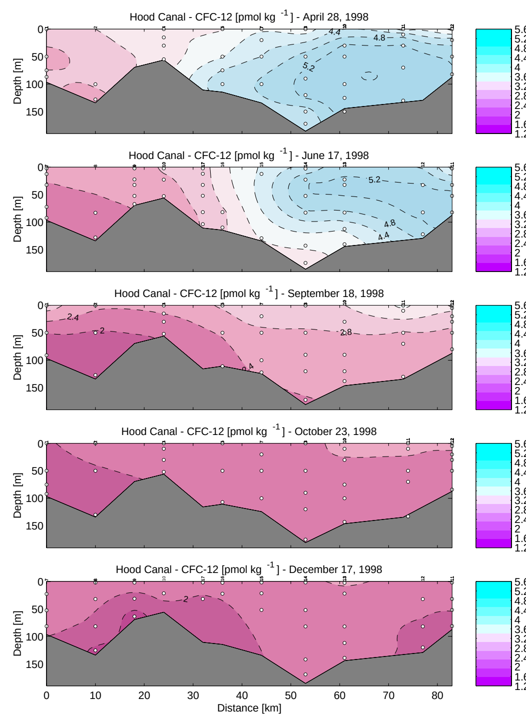


Figure 6 Vertical section of CFC-12 concentrations (pmol kg-1) in Hood Canal for

The distribution of CFCs in Hood Canal can be used in models to separate the contribution of the overturning circulation to the dissolved oxygen distributions from the contribution of respiration. During April-December 1998, the CFCs were measured on five of the cruises and provide sufficient temporal resolution to calculate flushing rates. The CFC-11 data (Fig. 5) reveals a small contrast between the inflow and the waters within the basin, however CFC-12 concentrations within the deep water of Hood Canal reveal a large contrast (Fig. 6). There appears to have been a release of CFC-12, possibly from a discarded refrigerator, within the deep layer. CFC-12 concentrations are 250% saturated relative to the atmospheric concentrations! The only way for this excess CFC-12 to leave the deep layers is to be entrained into the upper layer and then escape to the atmosphere through gas exchange. In April 1998, even the upper layers outside the sill are supersaturated with CFC-12 with respect to the atmosphere.

Box Model

A box model of the lower layer of Hood Canal can be used to determine flushing rates based upon the CFC inventories. Because of the contamination signal, calculations using CFC-12 will have a much higher signal-to-noise than those using CFC-11. This calculated flushing rate can then be applied to distributions of non-conservative properties to determine rates associated with biological processes. The model deep layer is 43 km long and includes the volume below 20 m. It is assumed to be of uniform width. The volume of water flowing into the box over the sill, Φ_{in}, is equal to the volume entrained into the upper layer Φ_{up} – mixing between the two layers is assumed to be negligible. Implicit in this assumption is that the river input and precipitation minus evaporation terms are much smaller than the flushing rate. The concentrations of the incoming water, C_{sill}, is an average of concentrations in the station on the sill and the two adjacent stations. Since there is a vertical gradient of CFC-12 concentrations within the deep Hood Canal box, the concentrations associated with the water entrained into the upper layer are the average concentrations of waters just below the upper layer (C_{bml}, between 20 and 40 m depth) rather than the average concentrations within the entire deep Hood Canal box. The equation can be solved for the average flushing rate between cruises. The concentrations associated with the fluxes are averaged with respect to time (i.e. averages of C_{sill} and C_{bml} for the two cruises). V_{dh} is the volume of the deep layer. The

$$V_{dh}\frac{\partial C_{dh}}{\partial t} = \Phi_{in}C_{sill} - \Phi_{up}C_{bml} + J$$

equation is solved for the volumetric flux, Φ, which can then be applied to other properties and solving for J, the source or sink term. J is 0 in the case of CFC-12. The calculated flushing rates for April – December 1998 range from 900 – 3300 $m^3\ s^{-1}$ with associated residence times within the deep Hood Canal of 40 to 150 days in the deep Hood Canal (Table 1). The time-weighted mean flushing rate is 1800 $m^3\ s^{-1}$ which compares favorably to the results of a reflux model (Cokelet and others 1992). These authors report a range of 1500 – 3600 $m^3\ s^{-1}$ for the volumetric flushing of Hood Canal based upon hydrographic data from 1951-1956.

Table 1. Results from the box model calculations for the deep Hood Canal box in 1998. Nutrient data were not collected on the same cruise as CFCs in April 1998 so no values are reported for the source term.

Time Interval	**Flushing Rate ($m^3 s^{-1}$)**	**τ (days)**	**J – O_2 (μmol $kg^{-1}s^{-1}$)**	**J - NO_3 (μmol $kg^{-1}s^{-1}$)**	**J – PO_4 (μmol $kg^{-1}s^{-1}$)**	**J – NH_4 (μmol $kg^{-1}s^{-1}$)**
April - June	890	146	-6.6×10^{-6}			
June - September	1910	68	-1.41×10^{-5}	7.7×10^{-7}	7.2×10^{-8}	-3.2×10^{-7}
September - October	3280	39	-1.09×10^{-5}	3.9×10^{-7}	6.2×10^{-8}	-2.8×10^{-7}
October - December	1660	78	-7.3×10^{-6}	3.6×10^{-7}	3.0×10^{-8}	-8.0×10^{-9}

Source and sink terms for the dissolved oxygen and nutrients are also listed in Table 1. The highest oxygen utilization rates occur in the June to September time period consistent with the time of highest primary productivity. The rates vary by a factor of two between summer and fall. Nutrient production is highest when oxygen utilization is highest. These oxygen utilization rates can be converted into estimates of the export primary productivity of the overlying waters using the assumption of the Redfield ratio for converting oxygen to carbon (-138:106). The oxygen utilization rates also need to be corrected for the conversion of the ammonium flux into nitrate within the deep layer (O2:NH3=2:1). The remainder of the oxygen utilization is assumed to result from respiration of organic matter produced in the upper layer. Integrating oxygen utilization rates versus depth for the model and converting from oxygen to carbon units via Redfield yields an estimate of export production from the upper layer in units of mg C m^{-2} d^{-1}. These values range from 640 – 1300 mg C m^{-2} d^{-1}.

We compare these export production values to total primary production for 1998 (Table 2). Primary production within the surface euphotic zone was measured at three stations in Hood Canal via ^{14}C uptake experiments incubated for 24 hours on the same cruises CFCs were measured. The measured values reported in Table 2 are an average of three stations per cruise and averaged for the two cruises. We recognize that there are many assumptions in converting instantaneous measurements into long-term averages which are likely to be invalid. However for a rough estimate of the relative size of the export production, these values will suffice. For 1998, the average export ratio (e-ratio, = export/total production) was 24%. However, strong seasonal variation is apparent and reflects a pattern typical of a temperate system dominated by macrograzers. There is moderate (~30%) export during the summer (June-October) with strong particle export during fall, presumably reflecting export of the fall bloom via a large population of fecal pellet producing macrozooplankton. Conversely, in spring, the macrozooplankton population is relatively small in abundance and export relative to total production is low. Assuming our measurements represent appropriate times and space scales in order to calculate an annual Hood Canal budget, this implies an f-ratio on the order of 25%, which is reasonable for a coastal system with nutrient-limited production.

Table 2. Comparison of primary productivity measured using ^{14}C d uptake during expeditions and export production calculated from integrated oxygen utilization rates derived from box model. The ratio of these two quantities is equivalent to the f-ratio.

Time Interval	**Measured Total Primary Productivity (mg C m^{-2} d^{-1})**	**Calculated Export Production (mg C m^{-2} d^{-1})**	**Export Production/ Total Production**
April-June	6830	640	0.09
June-September	5300	1300	0.25
September – October	2920	990	0.34
October – December	920	700	0.76
Average April - December	4220	970	0.23

Conclusions

Hood Canal flushes much more slowly than the Main Basin of Puget Sound, therefore it is possible to carry out studies on its deep circulation with monthly temporal resolution. There is a large amount of variation in the flushing rate of Hood Canal during the course of a year, as well as a large amount of interannual variability. The development of low dissolved oxygen concentrations is a result of not only biological processes, but also the timing of and dissolved oxygen concentrations associated with the flushing process. In general, the rate of oxygen utilization due to respiration will be higher in summer. However, even in 1998 when the flushing of the deep water began earlier than normal, oxygen remained relatively low throughout the deep basin. One possible reason for this is that the high nutrients which had built up over the winter were mixed into the surface layer by the flushing, resulting in increased primary productivity in the surface layer with an increase in the rain of particulate matter to the deep layer.

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